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Final Report:
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Formation flying missions are continually growing in size and complexity, and the requirement for ground-based demonstration of distributed systems grows with them. However, simulating the on-orbit environment shared by a group of satellites is a difficult task. The primary purpose of this DURIP project was to establish a Distributed Attitude Control Systems Simulator (DSACSS) in the Space Systems Simulation Laboratory (SSSL) at Virginia Tech. The DSACSS comprises two spherical air bearing spacecraft simulators manufactured by Space Electronics, Inc. in Berlin, CT. One of these simulators was purchased with internal VT funding and the second was purchased as part of this DURIP project. This report describes the state of the art of existing spacecraft simulators, the Distributed Spacecraft Attitude Control System Simulator, as well as several projects that we are undertaking with this unique new facility.

Introduction

Spherical air bearings are one of the most common devices used in spacecraft attitude dynamics research because they (ideally) provide unconstrained rotational motion. As the name implies, the two sections of the bearing are portions of concentric spheres, machined and lapped to small tolerances. One spherical section rotates on an air film bounded by the other section in three degrees of freedom. The rotating surface is rarely a 4π steradian sphere, as equipment affixed to the bearing limits the range of motion. Of course, other mechanical arrangements can serve a similar purpose — ball-and-socket joints, for example — but air bearings yield much lower friction.

Virginia Tech has developed a unique new facility comprised of two spherical air-bearing platforms. The uniqueness of this system stems not from particular individual capabilities of either platform, but rather from the ability to demonstrate decentralized control algorithms. Coupled with a third, stationary system, the Distributed Spacecraft Attitude Control System Simulator (DSACSS) provides an experimental facility for attitude control simulation of a three-satellite formation.[14]

The DSACSS only provides attitude freedom; the pedestals themselves cannot move. A planar air bearing could be used to recapture the relative orbital dynamics of the formation. Such testbeds provide one rotational and two translational degrees of freedom; the other two axes of rotation and out-of-plane motion are arguably less important in the investigation of relative orbital dynamics, at least for the level of effort required. There are several contemporary planar air-bearing facilities being used for the evaluation of formation flying algorithms.[5,6,8,15,16]

The most elaborate air-bearing systems combine these two types of motion into simulators that provide up to six completely unconstrained degrees of freedom. Marshall Space Flight Center's Flight Robotics Laboratory, described by the NASA Federal Laboratory Review in 1994 as "a facility that provides a quality, capability, capacity, product, technology, condition, or process recognized by the world aerospace community as among the best in the world" has a 44 ft × 86 ft precision floor. The Air Bearing Spacecraft Simulator used on the

planar floor provides a 400 lb payload six degree-of-freedom motion via a floating spherical air bearing coupled with a cylindrical lift.[13] Lawrence Livermore National Laboratory has an ongoing effort to foster the development of autonomous, agile microsatellites: payloads up to 70 lb are provided full freedom in yaw, $\pm15°$ in pitch and $\pm30°$ in roll on their Dynamic Air Bearing test vehicle. The vehicle can then either be floated on a 5 ft × 25 ft glass top Dynamic Air Table or can be mounted on one of two perpendicular 50 ft Dynamic Air Rails. The linear rail system yields five relative (four individual) degrees of freedom for a pair of payloads.[9]

The Distributed Spacecraft Attitude Control System Simulator

The ideal spherical air-bearing testbed would allow its payload unconstrained angular motion in three axes. Actually providing this rotational freedom is difficult and in practice requires constraining payload volume. "Tabletop" style platforms (Figure 1a) provide full freedom of spin in the yaw axis but pitch and roll motion are typically constrained to angles of less than $\pm90°$. Tabletops mount to the flat face of a hemispherical bearing, and components then mount to this structure. The "dumbbell" style requires a fully spherical bearing. This configuration offsets the mounting area away from the center of rotation by means of two opposing arms (Figure 1b). Dumbbell style air bearings greatly reduce structural interference within the rotation space of the payload and thereby provide unconstrained motion in both the roll and yaw axes. Note that the yaw axis for each configuration is defined to be nominally parallel to the gravity vector. For dumbbell systems, the roll axis is defined by the mounting arms; roll and pitch are indistinguishable for a tabletop system. The bearings illustrated in Figure 1 must of course each rest on top of a pedestal, not shown here for clarity.

(a)   (b)
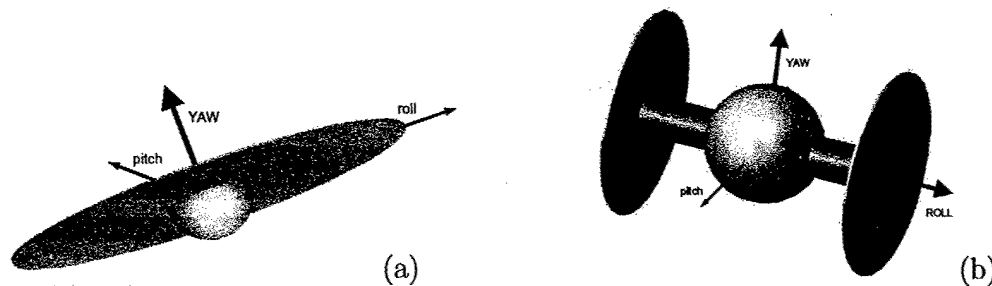
Figure 1: "Tabletop" and "Dumbbell" Style Air Bearings

The DSACSS consists of two air bearings from Space Electronics, Incorporated, one tabletop and one dumbbell style. Each can host a 300 lb payload. The tabletop platform provides full freedom in yaw and $\pm5°$ of tilt in pitch and roll. The dumbbell platform provides full freedom in both yaw and roll with $\pm30°$ of freedom in pitch. The formation is completed by a third (stationary) simulator. The tabletop simulator was purchased using internal VT funds, and the dumbbell simulator was purchased using the DURIP funds. Additional hardware for the system was also purchased using the DURIP funds.

At the core of each of the simulators (including the stationary one) is a PC/104+ form-factor computer. Each computer includes a 32-bit 133MHz Tri-M MZ104+ ZFx86 processor with 64MB of RAM. The processor board can control two EIDE devices and includes interfaces to both an ISA and a high-speed PCI bus (as per the PC/104+ standard), two

100/10 Base-T Ethernet ports, two USB ports, two serial ports, and one parallel port. The operating system (a lean, customized version of Slackware Linux) and command software is stored on a 288MB DiskOnChip solid-state memory device. Operational software is written in C/C++. Analog devices interface to the computer via a 16-bit Diamond Systems DMM-32 A/D board. Along with the 32 analog channels, the DMM-32 also provides 24 programmable-direction and 8 fixed-direction digital I/O lines for logic switching.

The three simulators communicate via the standard TCP/IP network protocol. Each computer system includes a Linksys WLAN-11 wireless network device. Every simulator can communicate directly with each of the other two through a wireless access point hosted by an external desktop computer. This desktop currently serves as the gateway to the internet for the simulator network; the stationary PC/104 system could also provide this functionality.

Each air bearing is equipped with three-axis accelerometers and rate gyros for attitude determination. These sensors are packaged as a BEI MotionPak II unit from Systron Donner Inertial Division. Interfacing with the PC/104 via a serial connection, this device can sense rates up to $\pm 75°/s$ and accelerations up to ± 1.5 g in each axis.

Both air bearings possess several control options. A suite of three custom aluminum/steel 0.075 kg m^2 wheels mounted on SM3430 Smart Motors can be used as either momentum or reaction wheel devices. Another SM3430 can be outfitted with a smaller wheel and slewed through a $\pm 45°$ range of angles as a control moment gyro (CMG). Currently only single-axis CMG control is planned, although the dumbbell system could host a pair of CMGs.

Another option for three-axis control is through a compressed air thruster system. Supplied by a 21 ft^3 nitrogen gas tank, the Evolutionary Concepts, Incorporated, solenoid valves can operate from the nominal system pressure (set prior to operation at values up to 100 psi) or the line pressure can be continuously varied via a computer-controlled variable-output Norgren regulator.

An important design consideration for air-bearing testbeds is to collocate the center-of-rotation of the bearing with the center-of-gravity (cg) of the system in order to mitigate the effect of gravity torques on the simulation. However, modelling the mass distribution of the payload to a sufficiently high resolution is prohibitively complex (e.g. including connectors, wiring, non-uniform density commercial components). Instead, each air bearing is equipped with three LPS-8-30 linear actuators from Servo Systems. Each actuator can support up to 30 lb of ballast across an 8 in. travel distance. Initially, these systems will be installed with much smaller (~ 2 lb) ballast weights and used exclusively for cg placement. Another possible control scheme entails traversing much larger (~ 20 lb) ballast weights for energy shaping by cg motion.

As shown in Figure 2, the tabletop system is essentially complete. The primary structure is a 3 ft octagonal aluminum honeycomb plate. Large components are mounted directly to threaded inserts installed in the honeycomb, and smaller components are clustered onto brackets. All commercial hardware for this system has been procured. Remaining tasks include final construction of the wiring harness and fabrication and balancing of the custom flywheels. The dumbbell system is less-developed; unlike the simple honeycomb plate construction, the dumbbell's primary structure must remain rigid through large slews in roll. If the structure is not sufficiently stiff the cg will oscillate in the gravity direction as the payload flexes while it rolls — the anisoelastic effect. The design of this structure is in progress, and most of the commercial components for this system were procured at the same time as those
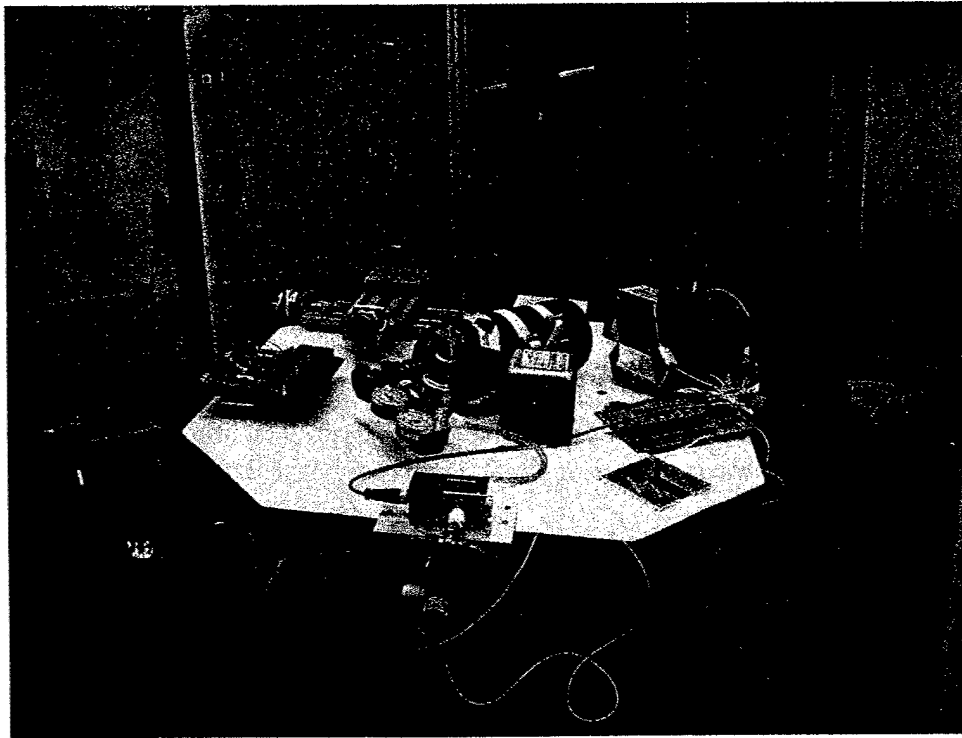
for the tabletop.

Figure 2: Virginia Tech's Distributed Spacecraft Attitude Control System Simulator

The hardware-interface level software for every component described above is written. The mission manager and message handling scheme has been designed and partially developed. Several techniques for system identification have been evaluated and are ready for real time testing. Thus, the tabletop system will be wholly operational by the end of the semester (May 2003). The dumbbell system will be operational by the end of the summer (August 2003). The DSACSS will be able to simulate a formation of three satellites at that time.

The DSACSS provides the flexibility to implement many types of control techniques. Novel individual platform control options include nonlinear compensation of an under-actuated system (such as simulation of a failed component), and coupled attitude control and energy storage techniques.[7,17] Formation control schemes could consider integrated orbit and attitude control[1] or coordinated pointing at terrestrial targets.[12]

The efficiency of a formation can be improved through the use of a decentralized controller by splitting the computational load among the flight computers and requiring less communication with a "master" system. Preliminary experimentation using NASA's Formation Flying Test Bed has validated this concept within the context of formation flying and relative orbit control.[2-4] The DSACSS can help to demonstrate the efficiency of decentralized attitude control techniques.

Projects Underway or Proposed

The tabletop simulator is being used as the base for an AFRL-sponsored project on "Base Motion Effects on Magnetic Bearings." Internal funding was obtained to purchase

an MB-Rotor Magnetic Bearing system from Revolve Magnetic Bearings, Inc. This system has been integrated into the flight computer and data acquisition system so that it can be controlled and measurements can be recorded through the PC/104 computer and accessed remotely using the wireless internet system. The student working on this project is Marcus Pressl, who is completing his M.S. thesis and plans to stay for a Ph.D. We plan to present results at the next AFRL/NASA Flywheel Workshop.

Because the DSACSS air bearings cannot provide translational motion, the orbital dynamics is being simulated with a two-body model for orbit propagation. A possible extension of this technique is to propagate the formation's orbit using a commercial software simulator such as FreeFlyer or Satellite Tool Kit. Either of these programs would provide orbital state data along with environmental parameters. A much more interesting idea is to maintain the hardware-in-the-loop experimental nature of the simulation by linking with the orbit simulation capabilities of NASA Goddard's Formation Flying Test Bed (FFTB), and we have submitted a proposal to Goddard to support such an effort. The student who is working on this interface is Jana Schwartz, who is a Ph.D. candidate, NSF Fellow, and Amelia Earhart Fellow.

Our implementation of a control moment gyro on the simulators is being supported by Honeywell, based on their interest in our work on using different actuators to control attitude motion.[7] In this project, we are developing control laws to use CMGs for large-angle rotations while using momentum wheels to correct attitude errors during the maneuvers. The student who is working on this project is an M.S. candidate, Eugene Skelton. He is making excellent progress on implementing the hardware and control laws and we plan to present results at the Astrodynamics Conference in August 2003.

Virginia Tech also has a large-scale virtual reality system: the Cave Automatic Virtual Environment (CAVE). The CAVE software makes use of a shared memory architecture among the many computers — the PC/104 on the tabletop will access and update this memory space during the experiments. An outstanding undergraduate is working on developing CAVE interface software for the two simulators, so that a user can visualize and control the simulators from within the immersive CAVE environment. The student who is working on this project is Michael Shoemaker, a junior, who interned with a Japanese Robotics Laboratory last year.

A similar undergraduate project involves a combination of manual and automatic control for docking. A junior, Cengiz Akinli, is developing the hardware, software, and control algorithms to implement a person-in-the-loop pointing control system specifically for docking of spacecraft. While this concept itself is not novel, the implementation will be a showpiece for the laboratory, and the experience that Mr. Akinli gets with the project will prepare him for graduate studies.

Publications

The primary publication related to this project is the survey paper[14] which is to be presented at the Space Flight Mechanics Meeting in February 2003. This paper has also been submitted to the *Journal of Guidance, Control and Dynamics* for publication in the series of review articles on History of Key Technologies. Software development for the simulators is also described in Refs. 18 and 1. Additional papers will be presented at the Astrodynamics Conference in August 2003.

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